Available at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

Assessment of straw biomass feedstock resources in the Pacific Northwest

Gary M. Banowetz[a,*], Akwasi Boateng[b], Jeffrey J. Steiner[c], Stephen M. Griffith[a], Vijay Sethi[d], Hossien El-Nashaar[a]

[a]US Department of Agriculture, Agricultural Research Service, National Forage Seed, Production Research Center, 3450 S.W. Campus Way, Corvallis, OR 97331, USA
[b]US Department of Agriculture, Agricultural Research Service, Eastern Regional Research Center, 600 E. Mermaid Lane, Wyndmoor, PA 19038, USA
[c]US Department of Agriculture, Agricultural Research Service, National Program Staff, GWCC, 5601 Sunnyside Avenue, Beltsville, MD 20705-5140, USA
[d]Western Regional Research Institute, Laramie, 365 North 9th Street, Laramie, WY 82072, USA

ARTICLE INFO

Article history:
Received 25 May 2006
Received in revised form
13 December 2007
Accepted 17 December 2007
Available online 8 February 2008

Keywords:
Grass straw
Wheat
Biomass resources

ABSTRACT

Straw that is produced as a coproduct of cereal grain and grass seed production on 24,000 km^2 in the Pacific Northwest states of Idaho (ID), Oregon (OR) and Washington (WA) has potential as a bioenergy feedstock. Previous attempts to develop approaches to convert straw to energy based on transporting straw to a conversion facility were uneconomical. Rising energy prices and the availability of new technologies have renewed interest in converting these lignocellulosic residues to energy products, especially liquid fuels [Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply, 2005. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf (website accessed December 2007). [1]], but information on the distribution of these resources is lacking. Development of an economic approach to convert this straw to energy will require an assessment of the regional distribution of available straw to identify an appropriate scale of conversion technology that optimally reduces straw collection and transportation costs. We utilized county-scale US Department of Agriculture (USDA) National Agricultural Statistical Service (NASS) data to quantify total grass seed and cereal straw production in each county of ID, OR and WA, subtracted the county-specific quantity of field residue for each crop, and developed an estimate of available straw, that remaining after sufficient straw is returned to the soil for conservation. At current straw yields, over 6.5 Mt of straw in excess of that required for conservation purposes are available in the region. This straw is distributed across the landscape at an average density of 2.4 $Mg\,ha^{-1}$ and in many locations will require small- or local-scale technology to enable economical conversion of the feedstock to energy.

*Corresponding author. Tel.: +1 541 738 4125; fax: +1 541 738 4127.
E-mail address: banowetg@onid.orst.edu (G.M. Banowetz).
0961-9534/$ - see front matter
doi:10.1016/j.biombioe.2007.12.014

1. Introduction

Coordinated efforts to develop dedicated energy crops like switchgrass for the US and other parts of the world are in progress [2–4]. Potential exists to produce energy crops in the Pacific Northwest of the US including Idaho (ID), Oregon (OR) and Washington (WA), but to be successfully adopted they will have to provide greater economic return than existing cropping systems that are already profitable. Whether energy crop production will displace current cropping systems is unknown, but there is potential to convert lignocellulosic residues that are produced in existing operations into energy products [5,6]. Approximately 24,000 km^2 of straw-producing cereal grain and grass seed production occurs in the region [7]. In the past, much of this biomass was burned because markets for straw were limited. During the past 15 years, air-quality regulations sharply reduced the use of burning and created a need for productive uses of the straw. With appropriate conversion technologies, this straw could serve as feedstock for energy production [8,9]. Not all of the straw is available for alternative uses because some should be returned to the soil as residue to prevent erosion and enhance soil quality [10,11]. Previous efforts were made to convert straw to energy [5,6], but at that time, available technologies did not produce energy at costs competitive with existing energy sources. Since that time, increased demand for and cost of transportation fuels has renewed interest in the use of lignocellulosic agricultural residues to produce energy. Compared with other potential uses for straw, energy is an attractive market because of growing demand and existing delivery systems. Furthermore, since the production costs of straw are recovered from the primary seed and grain business operations, residues used for energy represent value-added income to already profitable enterprises [8]. This differs from dedicated energy crop systems where all costs and profit must be recovered from the biomass energy crop. The availability of significant sustainable quantities of straw provides opportunity for energy production from biomass that is already being produced.

Previous efforts to evaluate the potential for converting straw to energy based their analyses on a model requiring transport of the feedstock to a centralized conversion facility [12,13]. A significant barrier to economical energy production in this model is the cost of collecting, handling and transporting feedstock to a distant facility. One alternative approach to reduce these costs, particularly the cost of transportation, is to perform the conversion on smaller-scale equipment on or near the farm where the straw is produced [8]. In some locations, local-scale technology shared by multiple farm enterprises may be appropriate. A detailed assessment of straw distribution within the region is needed to identify an appropriate scale of conversion that minimizes transportation costs and other energy inputs. In addition to assessing the distribution of straw in the region, there is need to quantify the net quantities of straw available after residue requirements for conservation purposes have been met.

The purpose of this study was to quantify straw produced by cereal grain- and grass seed-producing operations in ID, OR and WA and determine the net straw availability after conservation requirements have been met. A county-by-county analysis of the three states was conducted and net available straw was calculated utilizing a US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) tool to quantify county-specific residue requirements.

2. Methods for calculation of total and available straw feedstock

2.1. *Cereal straws*

County-by-county production acreages and average irrigated and dryland grain yields for barley, oats and wheat were obtained from the 2004 USDA National Agricultural Statistical Services (NASS) database [7]. Straw production data were not included in the database because straw yield is not generally quantified at harvest. The quantity of straw generated by cereal grain production was estimated on the basis of grain yields utilizing the USDA NRCS Soil Condition Index worksheet [14]. Site-specific residue equivalent values calculated by the NRCS Soil Condition Index utilizing county-specific grain yields were used as a guideline for the amount of residue that should be returned to the field to maintain soil fertility and prevent erosion. The residue equivalent value was subtracted from the total straw production to provide a conservative estimate of available straw for the region.

2.2. *Straws from grass seed production*

Significant quantities of straw also are generated by grass seed production that occurs on over 2400 km^2 in the region. Production acreage and yield data for individual grass seed crops not available from the NASS database were supplemented by State Extension Service data [15]. Straw yield calculations generated by the NRCS Soil Condition Index Worksheet significantly understated the amount of straw relative to published multiple year field data for perennial ryegrass (*Lolium perenne* L.), tall fescue (*Schedonorus phoenix* (*Scop.*) *Holub*) and the fine fescues (*Festuca* spp.) ([16]; Table 1). As a consequence, the published quantities of straw were utilized to estimate straw production in these crops. Similarly, straw production for irrigated Kentucky bluegrass (*Poa pratensis* L.) and dryland annual ryegrass (*Lolium multiflorum* Lam.) was approximated utilizing data from previously published field trials ([17,18]; Table 2). Straw production for non-irrigated Kentucky bluegrass was derived from unpublished data representing 3 years of trials conducted in commercial production fields in Spokane County, WA. Straw production estimates for orchardgrass (*Dactylis glomerata* L.) and bentgrasses (*Agrostis* spp.) were based on unpublished data from non-irrigated field trials conducted at the Oregon State University Hyslop Research Farm in western Oregon where orchardgrass and bentgrass straw production was quantified for 5 and 1 year, respectively (Table 2). Average yield data for these crops were used to calculate total straw production based on published acreage totals. The NRCS Soil Condition Index was then used to calculate residual equivalent values on a county-specific basis and subtracted from total straw production to provide estimates of available straw.

Table 1 – Straw yield for three grasses during establishment and three harvest years in direct seeded and tilled fields. Yields presented for harvest years represent combined data from direct seeded and tilled fields because there were no significant differences between establishment methods[a]

Crop	Establishment year yield ($Mg\,ha^{-1}$)		Yields during harvest years ($Mg\,ha^{-1}$)				
	Direct seed	Tillage	P	Year 1	Year 2	Year 3	P
Perennial ryegrass *Lolium perenne*	8.31	8.46	n.s.[a]	7.66	9.19	8.30	***
Tall fescue *Schedonorus phoenix*	12.28	12.87	n.s.	13.92	12.06	9.27	***
Creeping red fescue *Festuca rubra*	5.89	6.83	n.s.	4.94	7.54	7.27	***

n.s. = not significant at $P = 0.05$.
*** = significant at $P = 0.001$.
[a] Data from Steiner et al. [16].

Table 2 – Multi-year straw production data for species of grasses grown for seed in the Pacific Northwest

Species	Production location	Average ($n = 3$) straw yield ($Mg\,ha^{-1}$)
Kentucky bluegrass *Poa pratensis*	LaGrande, OR Irrigated[a]	18.22±0.09
Kentucky bluegrass *Poa pratensis*	Spokane County, WA Non-irrigated	7.49±0.31
Orchardgrass *Dactylis glomerata*	Willamette Valley of western Oregon[b]	6.79±1.01
Bentgrass *Agrostis* sp.	Willamette Valley of western Oregon[c]	9.74±1.03
Annual ryegrass *Lolium multiflorum*	Willamette Valley of western Oregon[d]	8.94±0.79

[a] Data from Griffith and Murray [17].
[b] Mueller-Warrant [30].
[c] Mueller-Warrant [30].
[d] Data from Griffith et al. [18].

Table 3 – Straw production from cereal grain enterprises in the Pacific Northwest states of Idaho, Oregon and Washington

State	Mt total straw production[a]	Mt available straw[b]
Idaho	5.87	2.34
Oregon	2.33	0.69
Washington	6.87	2.69
Totals for region	15.07	5.73

[a] Total straw yield from cereal grain production was calculated fro 2004 grain yields reported by USDA National Agricultural Statistics Services utilizing the USDA Natural Resources conservation Service Soil Condition Index worksheet.
[b] Available straw represents total straw production minus the residue equivalent value calculated for each location by the Soil Condition Index worksheet. The residue equivalent value is the calculated amount of straw required to maintain soil quality.

3. Results and discussion

3.1. Total and available cereal straw

Total straw production is impacted by the kind of crop, production practices used, local soil conditions and annual variations in weather during the production season [19]. Not all crop residues produced are available for biofuel production or other uses because it is desirable to return some residue to the soil to reduce erosion and maintain soil fertility [11,20,21]. The amount of straw residue recommended for return to the field depends upon local climate conditions, soil erodibility and nutrient needs, the slope of the land, and whether farmers participate in federal commodity programs that require specific amounts of residue to remain on the field. As a consequence, residue requirements are site- and cropping system-specific. The Soil Conditioning Index worksheet that accounts for much of the county-by-county variation in residue requirements was employed to calculate the amounts of total and available wheat, barley and oat straw for each state (Table 3). Over 15 Mt of straw are produced in the region and approximately one-third is available utilizing NRCS guidelines for returning straw residue to the fields. The states of WA and ID produce approximately 84% of the cereal straw in the region. In addition to straw resulting from wheat production, these estimates include that from oats, barley and grass seed enterprises, and consequently exceed previous estimates that only included wheat straw in the region [22,23]. Our approach to quantify residue requirements for conservation purposes differed from that of Kerstetter and Lyons [22] who based their estimates on returning 3360 or 5600 $kg\,ha^{-1}$ (3000 or 5000 lbs $acre^{-1}$) of straw to the soil for conservation purposes. We used single county-specific residue equivalent values calculated by the USDA NRCS Soil Conditioning Index worksheet, all of which fell within the range of residue they utilized and averaged approximately 4480 kg ha^{-1}.

3.2. Total and available straw from grass seed production

While significant quantities of straw from cool season grass production are available in ID and eastern WA, the majority (83%) of grass seed-production acreage occurs in the Willamette Valley of western OR and involves production of annual and perennial ryegrass and tall fescue ([15]; Table 4). An additional 5100 ha of bromegrass (*Bromus* spp.), fescue, orchardgrass and timothy (*Phleum pratense* L.) seed production occurs in the region, but were not included in our estimates because yield data were incomplete. Grass straw accounts for approximately 14% of the straw in the region. In contrast to cereal straw availability, approximately 45% of grass straw is available for alternative uses because much of the production occurs where straw yields are high relative to the calculated residual equivalent value.

3.3. Regional distribution of straw

Straw produced in ID is concentrated along the Snake River corridor and in the counties adjacent to the WA border (Table 5). Local quantities are greatly impacted by the use of irrigation, used most commonly in the Snake River corridor [24], a practice associated with greater straw and grain production. The majority of WA straw production is concentrated in the eastern part of the state including the Palouse region adjacent to the ID border, Spokane County and the Columbia Basin (Table 6). OR straw production is concentrated in the Willamette Valley, and in the wheat-producing region of the Columbia Basin (Table 7). While particularly abundant production occurs in localized areas, the availability of straw for bioenergy production could be impacted by local competing options for straw utilization.

Table 4 – Summary of straw derived from grass seed production in the Pacific Northwest states of Idaho, Oregon and Washington

State	Mt total straw production[a]	Mt available straw[b]
Idaho	0.11	0.04
Oregon	1.93	0.88
Washington	0.20	0.11
Totals for region	2.24	1.03

(http://soils.usda.gov/sqi/assessment/sci.html) was utilized to calculate the Residue
Equivalent value (REV), the calculated amount of straw required to maintain soil quality within each county where production occurred. Available straw represents total straw production minus the REV.
[a] Total straw from grass seed production was quantified utilizing 2004 harvested acreage data [15]. Average straw yields were determined in multiyear field trials (Tables 2 and 3).
[b] The USDA Natural Resources Conservation Service Soil Condition Index worksheet.

Table 5 – County-level combined cereal and grass straw production in Idaho

County	Mg total straw	Mg available straw
Ada	47,630	26,884
Bannock	80,257	24,012
Bear Lake	25,406	1583
Benewah	155,701	64,832
Bingham	609,386	315,107
Blaine	51,450	23,172
Bonner	203	20
Bonneville	171,641	139,706
Boundary	70,052	29,114
Butte	48,836	17,119
Camas	11,205	476
Canyon	177,775	105,867
Caribou	227,593	32,637
Cassia	480,607	238,976
Clark	32,552	13,605
Clearwater	28,527	5519
Custer	4706	1225
Elmore	49,058	24,551
Franklin	53,823	11,850
Fremont	270,770	76,671
Gem	19,128	8308
Gooding	44,691	22,063
Idaho	238,312	53,974
Jefferson	327,545	142,617
Jerome	152,651	77,891
Kootenai	49,081	18,947
Latah	339,277	127,060
Lemhi	1146	0
Lewis	307,086	95,907
Lincoln	53,669	21,025
Madison	241,557	85,138
Minidoka	330,234	161,923
Nez Perce	344,689	16,425
Oneida	59,851	5511
Owyhee	28,661	12,538
Payette	28,742	15,188
Power	348,133	142,729
Teton	108,657	23,098
Twin falls	332,903	192,387
Valley	3802	0
Washington	31,529	12,997

3.4. Competing uses of straw

Local and export markets provide alternate straw utilization options in certain parts of the region. Southern ID contains dairy operations that include over 475,000 cows concentrated in Ada, Canyon, Cassia, Gooding, Jerome and Twin Falls counties [25]. Significant diary production also occurs in Bingham, Franklin, Lincoln, Minidoka, Owyhee and Payette counties. These diary production enterprises provide a local demand for straw utilized as bedding (Paul Patterson, personal communication), but data that quantify current straw usage by dairies are not available. Fewer local markets

Table 6 – Total and available cereal and grass straw in Oregon

County	Mg total straw	Mg available straw
Baker	42,510	20,056
Benton	144,066	60,496
Clackamas	28,924	12,222
Crook	8885	5647
Gilliam	159,369	5516
Harney	3428	960
Jackson	660	0
Jefferson	93,314	62,455
Josephine	1802	262
Klamath	97,928	45,248
Lake	3543	857
Lane	109,229	48,541
Linn	739,714	312,088
Malheur	188,676	101,436
Marion	299,446	120,224
Morrow	254,927	36,064
Multnomah	2439	288
Polk	235,991	102,445
Sherman	246,080	60,267
Umatilla	845,914	270,652
Union	180,997	88,472
Wallowa	45,626	15,333
Wasco	148,619	31,141
Washington	152,508	68,853
Wheeler	1657	422
Yamhill	228,226	101,992

Table 7 – Total and available cereal and grass straw in Washington

County[1]	Mg total straw	Mg available straw
Adams	624,228	230,454
Asotin	50,126	0
Benton	255,916	79,265
Columbia	327,874	142,187
Douglas	352,358	125,261
Franklin	224,386	125,705
Garfield	297,521	128,504
Grant	510,817	132,164
Klickitat	74,253	9059
Lewis	1277	361
Lincoln	957,730	317,632
Okanogan	28,035	11,019
Spokane	581,171	270,365
Stevens	26,753	7821
Walla Walla	644,627	160,417
Whitman	2,048,808	1,045,666
Yakima	61,058	15,999

exist for straw produced in eastern WA and central and eastern OR, although markets for Kentucky bluegrass straw as an alternative livestock feed exist when alfalfa prices are elevated.

Currently, most Willamette Valley straw from perennial grass seed fields is exported as animal feed to Pacific Rim export markets [26], an enterprise in which the receipts from the straw, $45–50 per ton, are spread among straw brokers, straw storage, compression and transportation enterprises. In most cases, seed and grain producers receive minimal if any payment for straw from their fields. A relatively small percentage of the straw continues to be burned in the region under specific conditions.

3.5. *Limitations to straw-based bioenergy production*

A major obstacle to the economic conversion of straw into energy is the cost of transporting low-density straw to a conversion facility [21,22]. The widespread distribution of the straw in the region, combined with escalating transportation costs continue to provide a challenge to economic energy production. Some progress has been made in the development of small-scale thermochemical technology, but the economics of this approach remain unproven [8]. The current lack of financial return to straw producers contributes to an inability to guarantee reliable supplies of feedstock for operation of a centralized conversion facility, a necessary component to justify the high costs of capitalization [27]. Previous gasification reactors also had operational problems and limited durability due to corrosive constituents found in grass and cereal straws [28,29]. At higher operational temperatures where carbon conversion efficiency is high, feedstocks like straw that are rich in Si, K, Cl and other alkalis vaporize and react with other mineral components to form a sticky glass-like eutectic mixture referred to as slag.

While abundant straw resources exist in the PNW, suitable scalable technologies will be required in some parts of the region to reduce the costs of transporting the biomass.

4. Conclusions

Significant quantities of straw are being produced in the PNW by already profitable cereal grain- and grass seed-producing operations that have potential to provide value-added revenue directly to seed producers without diminishing the amount of residue needed for soil conservation purposes. Straw in the region is widely distributed at relatively low densities that, in many locations, make transportation of sufficient quantities to supply a centralized conversion facility uneconomical. In some locations, conversion technology scaled for on- or near-farm use has potential to reduce the costs of transporting the straw to an economical level, but the feasibility of developing small-scale conversion technology remains unproven.

Acknowledgments

We express thanks to Dr. George Mueller—warrant for providing data utilized in Table 2 regarding orchardgrass and bentgrass straw production. The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research

Service of any product or service to the exclusion of others that may be suitable.

REFERENCES

[1] Perlack RD. Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. 2005. ⟨http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf⟩ (website accessed December 2007).

[2] Kim S, Dale BE. Global potential bioethanol production from wasted crops and crop residues. Biomass and Bioenergy 2004;26:361–75.

[3] McLaughlin SB, Adams Kszos L. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. Biomass and Bioenergy 2005;28:515–35.

[4] Ericsson K, Nilsson LJ. Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass and Bioenergy 2006;30:1–15.

[5] Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. Journal of Power Sources 2002;111:1–22.

[6] Tijmensen MJA, Faaij APC, Hamelinck CN, van Hardeveld MRM. Exploration of the possibilities for production of Fischer–Tropsch liquids and power via biomass gasification. Biomass and Bioenergy 2002;23:129–52.

[7] USDA National Agricultural Statistical Service ⟨http://www.nass.usda.gov/#top⟩ November 2007.

[8] Boateng AA, Banowetz GM, Steiner JJ, Barton TF, Taylor DG, Hicks KB, et al. Gasification of Kentucky bluegrass (*Poa pratensis* L.) straw in a farm scale reactor. Biomass and Bioenergy 2007:153–61.

[9] Lv P, Yuan Z, Wu C, Ma L, Chen Y, Tsubaki N. Bio-syngas production from biomass catalytic gasification. Energy Conversion and Management 2006;48:1132–9.

[10] Nelson RG. Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States—rainfall and wind-induced soil erosion methodology. Biomass and Bioenergy 2002;22:349–63.

[11] Wilhelm WW, Johnson JMF, Karlen DL, Lightle DT. Corn stover to sustain soil organic carbon further constrains biomass supply. Agronomy Journal 2007;99:1665–7.

[12] Conklin FS, Young III WC, Youngberg HW. Burning grass seed fields in Oregon's Willamette Valley: the search for solutions. Oregon State University Extension Publication 8397; 1989.

[13] CH_2M Hill. Opportunities in grass straw utilization. Prepared for the Oregon Economic Development Department and Oregon Department of Agriculture, 1991.

[14] USDA Natural Resources Conservation Service ⟨http://soils.usda.gov/sqi/assessment/sci.html⟩ (website accessed November 2007).

[15] Young III WC. Grass and legume seed estimates for 2005. Crop and Soil News/Notes, Oregon State University Extension Service 2006;20:4–5.

[16] Steiner JJ, Griffith SM, Mueller-Warrant G, Whittaker GW, Banowetz GM, Elliott LF. Conservation practices in western Oregon perennial grass seed systems. I. Impacts of direct seeding and maximal residue management on production. Agronomy Journal 2006;98:177–86.

[17] Griffith SM, Murray GA. Evaluation of mechanical removal of post-harvest residue and enhanced ammonium nutrition of Kentucky bluegrass. In: Young III W, editor. Seed Production Research. Oregon State University Extension; 1995. p. 13–6.

[18] Griffith SM, Alderman SC, Streeter DJ. Italian ryegrass and N source fertilization in western Oregon in two contrasting climatic years. I. Growth and seed yield. Journal of Plant Nutrition 1997;20:419–28.

[19] Schillinger WF. Tillage method and sowing rate relations for dryland spring wheat, barley and oat. Crop Science 2005;45:2636–43.

[20] Wysocki D. Conservation farming and sustainability. In: Pacific Northwest Conservation Tillage Handbook. STEEP, Washington State University; 1990 [Chapter 1, No. 12].

[21] Graf A, Koehler T. Oregon cellulose-ethanol study: an evaluation of the potential for ethanol production in Oregon using cellulose-based feedstocks. Oregon Department of Energy; 2000.

[22] Kerstetter JD, Lyons JK. Logging and agricultural residue supply curves for the Pacific Northwest. Washington State University Energy Publication; 2001.

[23] Kerstetter JD, Lyons JK. Wheat straw for ethanol production in Washington: a resource, technical and economic assessment. Washington State University Energy Publication WSUCEEP2001084; 2001.

[24] Morse A, Zarriello TJ, Kramber WJ. Using remote sensing and GIS technology to help adjudicate Idaho water rights. 1990;56:365–70.

[25] National Agricultural Statistics Service. Agriculture in Idaho. 2006;9-06:1–4.

[26] Young III WC. 2004–2005 straw export data. Crop and Soil News/Notes. Oregon State University Extension Service 2005;19:3–5.

[27] Wright MM, Brown RC. Comparative exonomics of biorefineries based on the biochemical and thermochemical platforms. Biofuels, Bioproducts and Biorefining Journal 2007;1:49–56.

[28] Miles TR, Miles Jr TR, Baxter LL, Bryers RW, Jenkins BM, Oden LL. Boiler deposits from firing biomass fuels. Biomass and Bioenergy 1996;10:125–38.

[29] Hess JR, Thompson DN, Hoskinson RL, Shaw PG, Grant DR. Physical separation of straw stem components to reduce silica. Applied Biochemistry and Biotechnology 2003;105:43–52.

[30] Mueller-Warrant, G. (muellerg@onid.orst.edu) Personal communication, April 2006.